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Multi-agent Based Hierarchy Simulation Models of Carrier-based Aircraft Catapult Launch

Wang Weijun, Qu Xiangju*, Guo Linliang

School of Aeronautics Science and Engineering, Beijing University of Aeronautics and Astronautics, Beijing 100083, China

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Abstract

With the aid of multi-agent based modeling approach to complex systems, the hierarchy simulation models of carrier-based aircraft catapult launch are developed. Ocean, carrier, aircraft, and atmosphere are treated as aggregation agents, the detailed components like catapult, landing gears, and disturbances are considered as meta-agents, which belong to their aggregation agent. Thus, the model with two layers is formed i.e. the aggregation agent layer and the meta-agent layer. The information communication among all agents is described. The meta-agents within one aggregation agent communicate with each other directly by information sharing, but the meta-agents, which belong to different aggregation agents exchange their information through the aggregation layer first, and then perceive it from the sharing environment, that is the aggregation agent. Thus, not only the hierarchy model is built, but also the environment perceived by each agent is specified. Meanwhile, the problem of balancing the independency of agent and the resource consumption brought by real-time communication within multi-agent system (MAS) is resolved. Each agent involved in carrier-based aircraft catapult launch is depicted, with considering the interaction within disturbed atmospheric environment and multiple motion bodies including carrier, aircraft, and landing gears. The models of reactive agents among them are derived based on tensors, and the perceived messages and inner frameworks of each agent are characterized. Finally, some results of a simulation instance are given. The simulation and modeling of dynamic system based on multi-agent system is of benefit to express physical concepts and logical hierarchy clearly and precisely. The system model can easily draw in kinds of other agents to achieve a precise simulation of more complex system. This modeling technique makes the complex integral dynamic equations of multibodies decompose into parallel operations of single agent, and it is convenient to expand, maintain, and reuse the program codes.

Keywords: multi-agent system (MAS); multi-agent based modeling (MABM); tensor; carrier-based aircraft; catapult launch; hierarchy simulation model

1 Introduction

Carrier-based aircraft catapult launch is a complex system that involves multiple disciplines. The dynamics process of launching customarily consists of the movements of ocean, carrier, aircraft, atmosphere, and all their interactions. In addition, it also involves man-machine cooperation if considering the effects of pilot and/or commander. Concretely, the deck motion, catapult power, and ground effect of deck are related to carrier; the stroke of landing gear, power of engines, and pilot handling are related to aircraft; the special wind disturbance is related to the atmosphere[1-3]. Therefore, the catapult launch of carrier-based aircraft is a typical dynamics process of multibody with different inherent frequencies. Deck motion, characteristic of

*Corresponding author. Tel.: +86-10-82317519.
E-mail address: uq@buaa.edu.cn
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landing gear, power of engine, and wind disturbance mainly have effects on the process.

A large effort in calculation is generally needed for the dynamic system simulation of multibody that is usually with high orders, and is difficult to be expanded or to be separated for parallel computing[4-7]. With the development of computer technology, the bottleneck of data commutation is getting through. It is necessary now to choose an appropriate simulation modeling approach for designing a computation framework, so as to resolve these kinds of problems much easier.

Many researches on the carrier-based aircraft takeoff have been carried out, usually specialized in their own fields with supposing and simplifying the effects of other domains[8-9]. In Ref.[10], the model of carrier-based aircraft ski jump takeoff based on tensor is built, which is a simulation model of multibody including carrier, aircraft, and landing gear, whereas it is still built directly using coupled dynamic equations. However, some complex problems of large systems we may encounter usually result from multidisciplinary intersection. For instance, the synthesis of aerodynamic and control system, the match between carrier and aircraft system, and the coupling between environmental and human factors. For code reuse and unified description, to build a universal flexible and expansible hierarchy simulation model of carrier-based aircraft takeoff is necessary.

In recent years, the multi-agent based modeling (MABM), for complex system has become an important topic in a number of applications. By reason of the characteristics of complex system itself, agent-based modeling and simulation turn into a new promising research approach gradually. At present, the agent-based technique has become an effective means of researching complex system and building intelligent simulation models[11-12].

Through the use of multi-agent simulation modeling technique, the research of multibody is focused on the individual physical behaviors, more factors are easily described, such as human beings and atmospheric conditions. In addition, programming an agent-based model and capturing special phenomena of nonlinear complex system are much easier. This shows it is convenient to run a large scale system simulation with high fidelity through this modeling technique[12].

The modeling of flight dynamics with tensors is a new trend with many advantages, such as distinct physical meanings, rigorously strict structure, and the invariance under time-dependent coordinate transformations. It is easy to take more factors into consideration as well, for instance the deck motion, atmospheric disturbance, and stroke of landing gears[13-14].

To study the carrier-based aircraft catapult launch, an agent-based hierarchy simulation model of multibody with tensors is proposed in this article.

2 Hierarchy Model Based on Multi-agent System (MAS)

2.1 Catapult launching system

The standard method used for launching aircraft from carrier is the nose gear launch method, in that the aircraft is coupled to the catapult by means of a launch bar and a holdback bar located on the nose gear (Fig.1). Before launching, the carrier is steered against the wind as far as possible, the engine of aircraft is set at full throttle, and the elevator is set in the right position, then a good occasion is chosen to start launching according to the pitching motion of the carrier. During launching, the tow force applied on the aircraft builds up rapidly, as soon as the load limit of holdback bar is reached, the aircraft is released and the launching run is begun. At the end of the catapult power stroke, the aircraft automatically disengages from the catapult and continues the launch with its own power, until it runs out off the carrier and climbs up. In this process, the carrier motion induces the wind disturbance, and the aircraft is affected by the deck wind and the disturbance ahead of the bow.

The whole system of carrier-based aircraft catapult launch mainly consists of carrier, aircraft, atmospheric environment, and ocean. In more detail, the system involves catapult, the engine of aircraft, landing gears, pilot, and special wind disturbance.

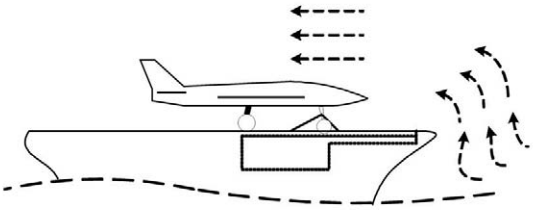

Fig.1 Components of catapult launch system.

2.2 Hierarchy domain model based on MAS

First, the real agent model, also called domain agent model, is built based on the integrality of system[15] and it is built through the observation, abstraction, and analysis of specific actions of complex system in different research fields. The whole complex system is described through the explication of its details, which includes agent's action rules and states, and the interaction among agents or between agent and environment.

Logically, the catapult launch system can be divided into four physical entities that interact with each other i.e. carrier, aircraft, atmosphere, and ocean. Each of them has its individual natural attribute, and there are obvious interrelations among them. Ocean acts on carrier to cause its motion; carrier acts on aircraft to support and restrict its takeoff; atmosphere not only provides the aerodynamic forces for aircraft, but also acts on carrier to bring forth the deck wind and the disturbance ahead of the bow, which affects the takeoff of aircraft.

Practically, the four entities involve more subentities, for example, the catapult belongs to carrier and the landing gears belong to aircraft. The interaction between catapult and landing gears is the key factor of the catapult launch process. Moreover, the subentities of carrier may also include takeoff commander, deck service staffs, whereas engine, pilot, instrument system, control system and the like may be included in aircraft. Therefore, the logical relationship of these entities can be expressed as in Fig.2.

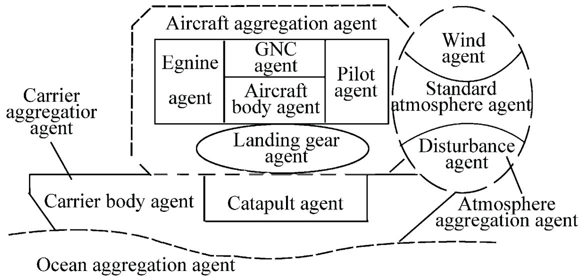

Fig.2 Domain agent model of catapult launch system.

In Fig.2, the domain model of catapult launch is composed of four aggregation agents i.e. carrier agent, aircraft agent, atmosphere agent, and ocean agent. In addition, these aggregation agents are further subdivided into some meta-agents. The carrier aggregation agent includes carrier body meta-agent and catapult meta-agent, in which the carrier body agent represents its motion characteristics and deck restrictions and the catapult agent brings forth the catapult power and its variance. The atmosphere aggregation agent relates to wind agent and disturbance of bow agent. The aircraft aggregation agent covers landing gear agent, aircraft body agent, engine agent, pilot agent and such. The nose gear and main gears are simplified as one landing gear agent. Thus, multi-agent models with two layers are formed.

For studying the issues of man-machine match and flight management of carrier-based aircraft takeoff, some meta-agents or the layers of the model can be brought in further, such as takeoff officer agent, deck service staff agent, and instrument system agent.

2.3 Communication within aggregation agent layer

Each agent has to communicate with others at regular intervals when running dynamics simulation. Within the aggregation agent layer, the ocean agent has main influence on carrier motion, whereas the ocean is hardly affected by carrier. The effects of aircraft and atmosphere on carrier are neglected for the mass of carrier is relatively huge. Whereas, carrier has overwhelming influences upon aircraft during catapult launching, which involve forces, displacements, velocities, and the like. Moreover, the atmospheric disturbance caused by the carrier may change the movement of aircraft to a certain extent.

Fig.3 shows the information flow of aggregation agent layer.

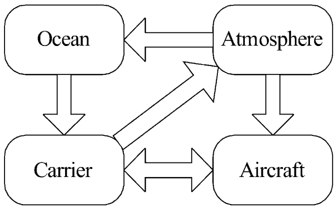

Fig.3 Communication among aggregation agents of catapult launching system.

2.4 Communication within meta-agent layer

The relationships among meta-agents are anfractuous. Along with the variation of environment, the characteristics of meta-agents change, and the number of mega-agents that interact directly with any mega-agent may also change. For example, the landing gear and the catapult usually interact with each other within only 2 s, then they detach from each other, and the data exchange between the two meta-agents will stop. If all meta-agents communicate with each other directly, the simulation mode will become conventional, which is not modularized and is hard to be deployed. Therefore, the meta-agents within one aggregation agent communicate with each other directly by information sharing. But, any two meta-agents, which belong to different aggregation agents exchange their information through the aggregation layer first, then perceive it from sharing environment, that is the aggregation agent. Thus, not only the hierarchy model is built, but also the environment perceived by each agent is specified. Meanwhile, the problem of balancing the independency of agent and the resource consumption brought by real-time communication within multi- agent system is resolved.

The information flow is shown in Fig.4.

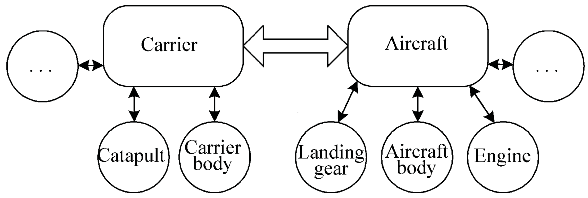

Fig.4 Communication among meta-agents.

3 Agent Concept Model Based on Tensor

Most motion agents are reactive agents, their actions or decisions are made according to their current conditions, no matter what the past states are[16]. Their concept models are formed primarily based on what they see and do, in particular, the dynamics equations and the perceived information are expressed with tensors. In Ref.[10], the Newton's second law and the theorem of moment of momentum in tensor forms of carrier-based aircraft are shown as Eq.(1) and Eq.(2):

$$F_B + m^{\mathrm{B}} g = m^{\mathrm{B}} D^{\mathrm{I}} (D^{\mathrm{I}} s_{BI}) \tag{1}$$

$$M_B = D^{\mathrm{I}} (l_B^{\mathrm{BI}}) = D^{\mathrm{I}} (I_B^{\mathrm{B}} \omega^{\mathrm{BI}}) \tag{2}$$

where F_B is the resultant external force acting on the centre-of-gravity (c.g.) of aircraft (the subscript B), and M_{B} is the resultant external moment of the force with respect to point B. F_B and M_B are tensors. $D^{\mathrm{I}}(*)$ is the time derivative of tensor * with respect to inertial frame (the superscript I). s_{BI} is the displacement tensor of the c.g. of aircraft with respect to the origin of inertial frame (the second subscript I). I_B^{B} is the inertia moment tensor of aircraft relative to its c.g., and ω^{BI} is the angular velocity tensor of aircraft frame with respect to inertial frame.

3.1 Ocean agent model

The ocean aggregation agent perceives the environment of atmosphere and responds accordingly, and it only acts on the carrier to change its position and postures[17].

3.2 Aircraft agent model

The aircraft body agent and the landing gear agent are involved in this aggregation agent model. The two meta-agents within the model communicate with each other or with other agents all through this model. The aggregation agent collects information that every meta-agent needs to perceive, which includes the state of each meta-agent and some data of other aggregation agents. Then, these meta-agents perceive the needed information on their own initiative.

(1) Aircraft body agent model

① Actions

In catapult launch process, the aircraft body agent model acts in terms of Newton's law as a dynamics system, it is expressed just as Eq.(1) and Eq.(2). The actions perceive the information (forces and moments) from the aircraft aggregation agent during every integral step, and then work out the dynamic response to react with its outside environment.

The following are the dynamics equations based on tensor:

$$F_{\mathrm{a,t,d}_i,\mathrm{r}_i}/m^{\mathrm{B}}+g=D^{\mathrm{I}}(D^{\mathrm{I}}s_{BI})=D^{\mathrm{I}}(D^{\mathrm{I}}s_{BS})+D^{\mathrm{I}}(D^{\mathrm{I}}s_{SI}) \tag{3}$$

$$M_{\mathrm{a,t,d}_i,\mathrm{r}_i}=D^{\mathrm{I}}(I_B^{\mathrm{B}}\omega^{\mathrm{BI}}) \tag{4}$$

Where $F_{\mathrm{a,t,d}_i,\mathrm{r}_i}$ denotes four different kinds of resultant forces, that is, aerodynamic forces, thrust, and the reaction forces, and constrained forces of landing gears, $M_{\mathrm{a,t,d}_i,\mathrm{r}_i}$ the resultant moments of those forces with respect to the c.g. of aircraft, s_{SB} the displacement tensor of the c.g. of aircraft with respect to the c.g. of carrier (the second subscript S), and s_{SI} the displacement tensor of the c.g. of carrier with respect to the origin of inertial frame.

② Perceived information

According to the equations given above, the following is the information that the aircraft body agent model needs to perceive.

A) Information inside the aggregation agent

Tensor related to aircraft engine: the thrust F_{t};

Tensors related to landing gears: the reaction forces and constrained forces at three mounting points, F_{d_i}, F_{r_i}, i=1,2,3;

The information related to pilot: the stick power and position, which will lead to a change in F_{a} and M_{a}.

B) Information outside the aggregation agent

The information related to atmosphere: the tensor v_{W} (velocity of wind) and the tensor $v_{\mathrm{W_d}}$ (velocity of disturbance), and the data of standard atmosphere used to work out the aerodynamic force F_{a} and moment M_{a}.

(2) Landing gear agent model

① Actions

The landing gear model is built as lumped masses in response to compression forces of the tires and the bumper struts, but the aerodynamic force is ignored. Three landing gears are treated as having single degree of freedom along the z axis of the aircraft body frame, whereas the other directions are treated as being rigid.

Taking the nose gear into account, the dynamic equation is obtained according to Newton's law:

$$m^{\mathrm{G_1}}D^{\mathrm{I}}(D^{\mathrm{I}}s_{\mathrm{G_1B}})=F_{\mathrm{d_1}}+F_{\mathrm{b_1}}+F_{\mathrm{r_1}}+m^{\mathrm{G_1}}g-m^{\mathrm{G_1}}D^{\mathrm{I}}(D^{\mathrm{I}}s_{\mathrm{BI}}) \tag{5}$$

where s_{G_1B} is the displacement tensor of the c.g. of nose gear with respect to the c.g. of aircraft. $F_{\mathrm{d_1}}, F_{\mathrm{b_1}}$, and $F_{\mathrm{r_1}}$ denote the deck reaction force, the load of bumper (including the air compression spring force, the hydraulic damping force, and friction/leakage damping forces), and the displacement constraining force (the counterforce of constraining force acting on aircraft).

In order to work out $F_{\mathrm{d_1}}, F_{\mathrm{b_1}}$, and $F_{\mathrm{r_1}}$, it is necessary to find out the kinematic relationship through the geometrical restriction relations of the landing gears, the deck, and the mass center of aircraft. The c.g. of landing gear, the c.g. of aircraft, the c.g. of carrier, and the contact point between the tire and the deck form a closed vector polygon (Fig.5), thus, the radius of the tires under pressure can be calculated.

The following shows the vector polygon of right main landing gear:

In Fig.5, s_{D_2S} is the displacement tensor of contact point D_2 with respect to the c.g. of carrier, s_{G_2B} is the displacement tensor of wheel axle (G_2) with respect to the c.g. of aircraft. Thereby, the tire radius can be expressed as

$$r_{D_2G_2}=s_{D_2S}-s_{G_2B}-s_{BS} \tag{6}$$

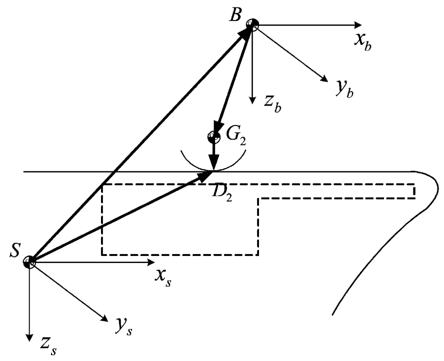

Fig.5 Closure of the vector polygon.

② Perceived information

A) Information inside the aggregation agent

Tensors related to the aircraft body: the displacement tensors s_{G_iB} of the wheel axles with respect to the c.g. of aircraft (i=1,2,3) and the displacement tensor s_{SB} and s_{BI}.

These tensors can be used to calculate the magnitude of compression and the constraining forces.

B) Information outside the aggregation agent

Tensors related to the carrier: the displacement tensors s_{D_iS} of the contact points with respect to the c.g. of carrier, the holdback force F_{h}, and the catapult tow force F_{c}.

3.3 Carrier agent model

As above-mentioned, the carrier aggregation agent model includes carrier body meta-agent and catapult meta-agent. The aggregation agent works as a bridge for the communication between the inside meta-agents and their communication with outside environment.

(1) Carrier body agent model

The model is built to describe the dynamics characteristics of carrier body. Its motion states can be figured out through its dynamic equations. The influence of aircraft that acts on carrier is ignored here. Time history of carrier motion is depicted according to the oceanic action[17].

① Actions

The position and posture of carrier in time sequence are worked out in accordance to certain frequency spectrum.

The position of aircraft and catapult bar are determined according to the dimensions of carrier.

② Perceived information

The oceanic movement.

(2) Catapult agent model

① Actions

The model is designed mainly for calculating the tow force of catapult acting on the aircraft.

If the weight of aircraft is given, the relationship between its endspeed and vapor stream pressure can be found from the performance curves of various catapults. In addition, the relation between the tow force of catapult and its corresponding stroke under different vapor steam pressures can also be found from the performance curves.

The force of tension is initialized prior to actual catapult firing. When fired, the release load of holdback bar is reached after approximately 0.2 s, then the tow force becomes a function of the shuttle displacement (the stroke) and the weight of aircraft

$$F_c = f(s_{DS}, m^{\mathrm{B}}) \tag{7}$$

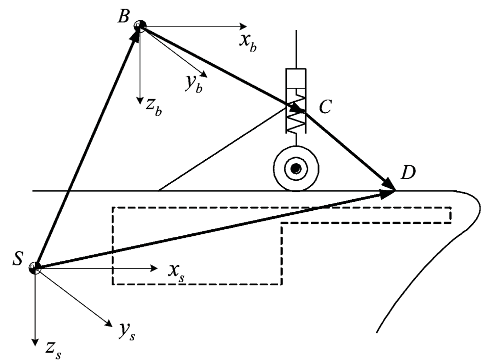

Fig.6 Closure of the vector polygon of catapult.

In Fig.6, point C is the towed point of catapult bar on nose gear, and D is the ideal contact point of catapult bar on the deck. The equation of the closure of the vector polygon can be expressed as

$$s_{DS} = s_{DC} + s_{CB} + s_{BS} \tag{8}$$

The precise stroke of catapult shuttle can be figured out through the above equation. In addition, the tow force acting on the aircraft can be calculated through Eq.(7).

② Perceived information

A) Information inside the aggregation agent:

The information related to carrier body: the dimensions and posture of carrier are used to find out the stroke of catapult shuttle.

B) Information outside the aggregation agent:

Tensors related to aircraft: s_{CB} and s_{BS}.

3.4 Atmosphere agent model

(1) Actions

The atmosphere can be disturbed by carrier and produce the deck wind and the disturbance ahead of the bow, and the corresponding data can be obtained with reference to the military specification MIL-F-1797A. Meanwhile, the standard atmosphere acts on the aircraft to bring forth the aerodynamic forces, which are calculated by aircraft body agent model.

(2) Perceived information

The velocity v_{SI} and the dimensions of carrier.

4 Simulations

The realization of entire simulation is just to run all these agent models, and a common timer needs to be set up for running the simulation. Each agent runs independently with its own integral rate following the ticks of timer. In this simulation process, every meta-agent perceives the needed information actively from its aggregation agent, and then sends its state message to the aggregation agent. Every aggregation agent perceives information from other aggregation agent models and deals with the communications among their inside meta-agents. Thus, the simulation can be run along the real time axis, and every agent keeps its independency.

Some results are shown in Fig.7 to Fig.14. The longitudinal deck motion, deck wind, disturbance ahead of the bow, ground effect and some other influence factors are considered in this launching simulation.

Fig.7 describes the time histories of the angle of attack α, pitch angle θ, and roll angle ϕ. Fig.8 shows the pitch rate q and roll rate p. Fig.9 shows the ground speed of aircraft when the speed of carrier is 10 m/s. Fig.10 shows the longitudinal flight path. These curves are obtained from the aircraft body agent. Fig.11 shows the time history of the pitch angle θ_s of longitudinal deck motion that resulted from the carrier body agent. Fig.12 shows the tow force of catapult, and Fig.13 shows the compressed travels of landing gears, where curve s_1 and curve s_2 represent the nose gear and the main gears, respectively. Fig.14 shows the disturbance wind ahead of the bow V_{z_w} and the deck wind V_{x_w}, which are calculated according to MIL-F-1797A.

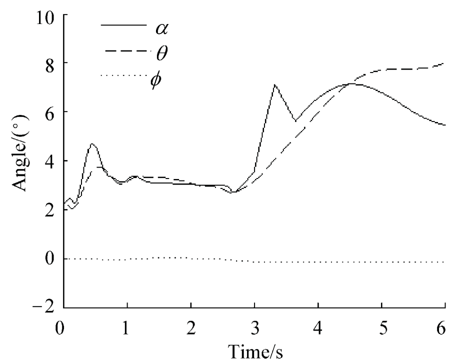

Fig.7 Attitude angle of the aircraft.

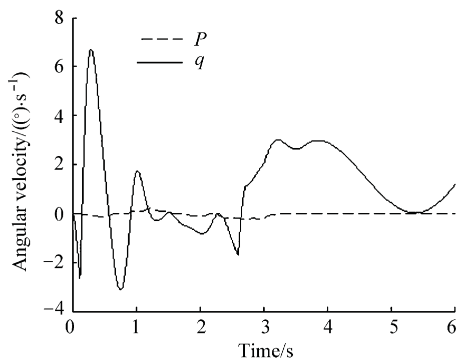

Fig.8 Angular velocity of the aircraft.

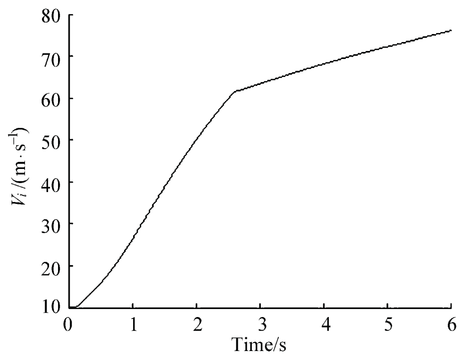

Fig.9 Ground speed of the aircraft.

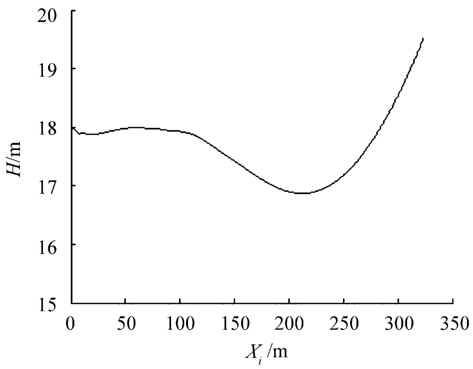

Fig.10 Aircraft flight path.

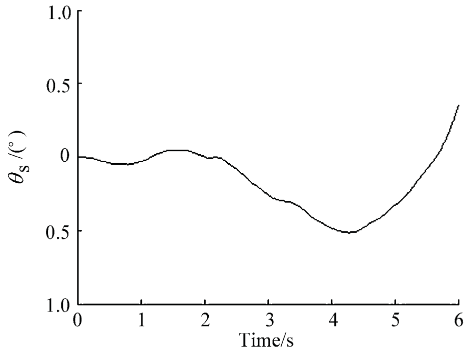

Fig.11 Pitch angle of the carrier.

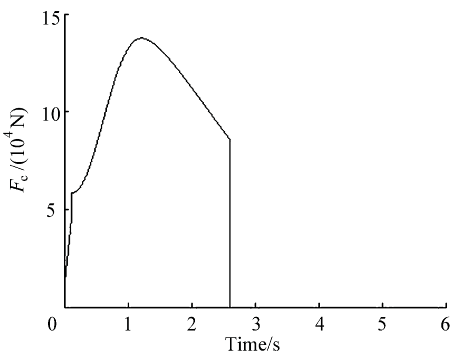

Fig.12 Tow force of the catapult.

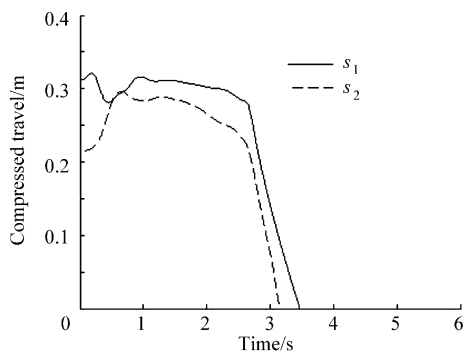

Fig.13 Some results of landing gears.

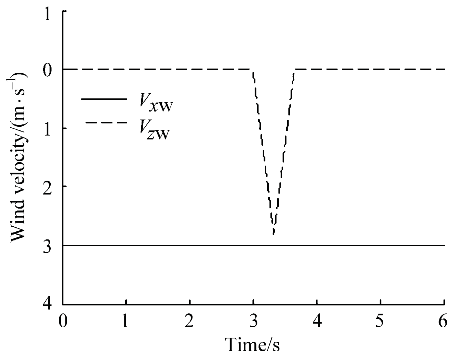

Fig.14 Some results of atmosphere agent.

5 Conclusions

The simulation and modeling of dynamics system based on MAS is of benefit to study the multidisciplinary intersection problems. The physical concept can be clearly defined and the logical hierarchy is more explicitly precise. The system model includes all reactive agents of motion entities; in particular, it can easily draw in kinds of deliberative agents of intelligent systems to achieve a precise simulation of more complex system. For instance the pilots or commanders coupled in the system, measuring and control modules with random disturbances and noises.

As viewed from the computer simulation, the multi-agent hierarchy modeling approach is advantageous to resolve the problems of carrier aircraft takeoff. The definition of agents and environments and their communications are precise and explicit. Compared with traditional techniques, this modeling technique makes the complex integral dynamics equations of multibodies decompose into parallel operations of single agent, and it is convenient to expand and maintain the simulation and easy to reuse the program codes. Furthermore, these codes can be abbreviated with the use of tensors, and by adding some self-checking codes into each agent the simulation can be verified and validated more easily.

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Biographies:

Wang Weijun Born in 1971, received B.S. and M.S. from Beijing University of Aeronautics and Astronautics in 1993 and 2000, respectively, and became a teacher there in 1993. His main research interests are flight dynamics and control, flight simulation, and modeling.
E-mail: wangwj@buaa.edu.cn

Qu Xiangju Born in 1956, she has been a full Professor since 2000 in the School of Aeronautics Science and Engineering of Beijing University of Aeronautics and Astronautics. Her research interests include flight dynamics and control, man-machine systems, flight path planning, and trajectory optimization.
E-mail: uq@buaa.edu.cn

Guo Linliang Born in 1982, he received M.S. from Beijing University of Aeronautics and Astronautics in 2007. His main research interests are flight dynamics and control, flight simulation, and modeling.
E-mail: guolinliangliang@163.com